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Report Title

Observations of Runoff Generation during Dry/Wet Season Transition in Panama

ABSTRACT

During 2005, the P.I. and graduate students installed an extensive network of instrumentation near Gamboa, Panama, for the purpose of making observations of hydrologic and hydrometeorological parameters at the hillslope scale. Instrumentation installed include an eddy-correlation flux system on a 36 m tall tower near Cerro Pelado, and throughfall troughs, soil moisture sensors, rain gages, interflow collector, piezometers, and surface flow measurement. Fundamental hypotheses were tested regarding changes in runoff efficiency during the early wet season. Results indicate that at the Gamboa study site, soil water hydrophobicity plays an important role early in the wet season. As the wet season advances, the role of hydrophobicity is diminished, while groundwater levels rise, increasing the occurrence of saturation excess runoff. During the most extreme rainfall event observed (150 mm of rainfall in 24 hours on Christmas Day, 2005), runoff occurred from upland areas likely due to mechanisms other than the traditional saturation excess runoff mechanism. These might include short-term perched water table due to high-intensity rainfall given the significant vertical change in hydraulic conductivities in the soils at Gamboa.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

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Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

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Inventions (DD882)

Foreword

Unfortunately, the inhospitable conditions of the tropics have historically led to a disparity of detailed scientific studies as compared to their temperate counterparts. Time takes on an entirely different meaning in this region of the world. Dense tropical jungle makes travel difficult, mere kilometer of travel may take well over an hour on foot. The Rio Chagres remained largely unstudied from a rigorous scientific standpoint before 1999. Fortunately that changed with the help of the U.S. Army Research Office and the U.S. Army Tropic Regions test center. A contingent of scientists and engineers from many disciplines began a concerted effort to further understanding of the Rio Chagres. The direct result of this group effort has been continuous field studies in the basin, an international scientific symposium in 2003, and a published book [Harmon, 2005].

From the hydrologic perspective the most exciting phenomena to investigate spring from features in the runoff records. Excellent stream gage records exist just upstream of Madden dam thanks to the presence of the Canal. This Chico gaging station defines the Upper Rio Chagres watershed, herein referred to as the URC. Several unique features are immediately revealed without having collected any specialized data. A typical year of runoff exhibits a pronounced dry season from late December until late April with little more than constant baseflow, as seen in Figure 1. Almost immediately after the wet season commences the hydrograph transitions to a state of flashy runoff. Digging a little further shows that the ratio of rainfall to runoff is typically highest at the beginning of the wet season. This is counter-intuitive since one might expect the large cumulative volume of rainfall later in the wet season would act to saturate the soil column enhancing higher runoff efficiencies. Furthermore, October and November are the months that on average have the highest rainfall totals. Another interesting feature of the hydrograph that we immediately noticed were step wise increases in the base flow levels during the wet season. Are there some storage compartments within the watershed that upon filling provide an additional transport of water? What role do seasonal transitions play in runoff generation in the tropics? These are just two questions that must be answered to further our understanding of the important hydrologic processes in this tropical catchment.

Gamboa is a small town located at the junction of the Rio Chagres with Gatun Lake. A study area on land near Gamboa that is controlled by the Smithsonian Tropical Research Institute, and the National Technological University of Panama, and the University of Panama. The study site is mountainous terrain, on the shoulder of a small mountain named “Cerro Pelado”. This site served as the setting for a highly detailed field study. To rigorously quantify many of the important contributions to the hydrologic cycle one must do so at a smaller, manageable scale. Hillslope scale catchment (< 1.0 km^2) studies were undertaken to quantify each of the potential pathways available to water from the time it enters the catchment as precipitation to the time it leaves as streamflow. Instrumentation was installed at Cerro Pelado includes:

- Eddy-covariance evapotranspiration flux, upon a 35 m tall tower
- Rainfall above the canopy using dual rain gages
- Rainfall interception by canopy using throughfall collector troughs
- Stem flow on a number of tree species
- Soil moisture at five depths, at four locations along the hillslope
- Throughflow at one 0.8 m deep interception trench
- Surface flows at four locations along the hillslope
- Groundwater tables at five locations along the hillslope
- Overland flow at one location near the toe of the hillslope

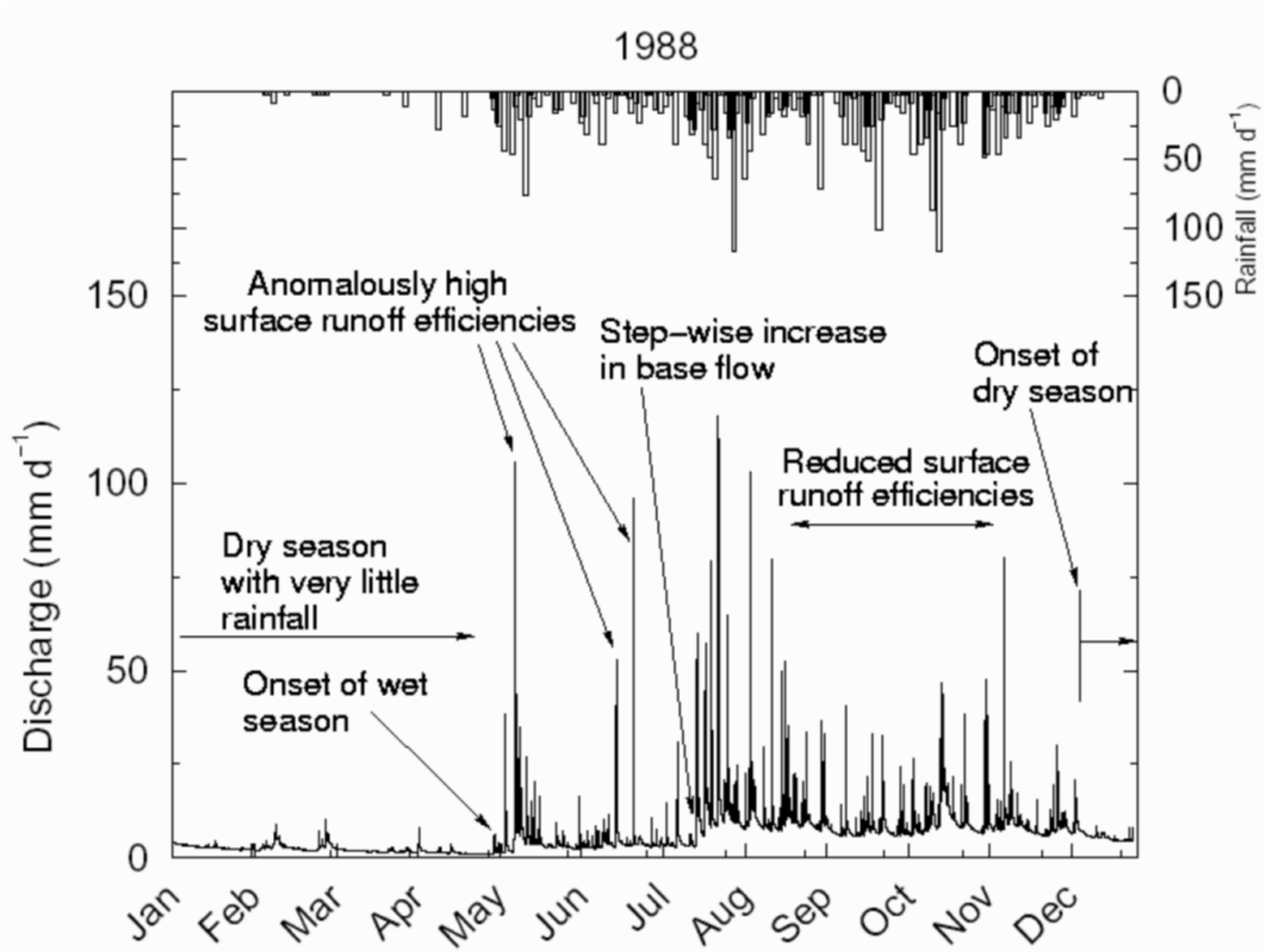

Figure 1: Annual Runoff Hydrograph, Upper Rio Chagres at Chico, for 1988

List of Appendixes, Illustrations and Tables (if applicable)

Statement of the problem studied

One important issue that this report details is that our predictive ability of runoff in the tropics will not improve until we can more accurately describe fundamental processes in tropical hydrology. Most rainfall-runoff models used in practice today were either developed for temperate locations or employ assumptions that are too generalized. Further, given the scarcity of data in the tropics it is unwise to expect that model application should provide an accurate prediction for the correct reasons without first undertaking some basic data collection to understand the system. In the more studied temperate areas the modeler can often use with standard models in ungaged basins. In the tropics, standard hydrologic models fail when applied to the data set shown in Figure 1. This report describes some of the measurements that were made to improve our understanding of the hydrology of the seasonal tropics in Panama.

Summary of the most important results

Precipitation

The convective nature of the storms is reflected in the summary statistics of the precipitation where the mean storm duration is 2.6 hours. Statistics were computed for a total of 96 rainfall events during the period May 26 – October 15, 2005.

	Mean	Median	Std Deviation	Minimum	Maximum
Duration [h]	2.6	2.2	2.1	0.2	11.5
Total [mm]	8.0	4.3	10.5	0.3	49.0
Intensity [mm/h]	4.4	2.1	5.6	0.3	28.8

Table 1 Summary statistics for storm duration, total, and average intensity at the tower gages from 96 events during the period May 26 - October 15, 2005.

Throughfall

Throughfall percentage of gross rainfall was computed on both a weekly and event basis for comparison. Unfortunately, numerous equipment failures essentially rendered TF1 data almost non-existent requiring the analysis to be limited to the collection system located closest to the tower. This throughfall system was operational approximately the same amount of time as the tower with one gap in data due to data logger failure of approximately two weeks. Therefore the data analysis consists of 16 weekly comparisons or 73 individual rainfall events to compute interception percentages. Averaging the ratio of *TF/P* for each of the events sample yields a ratio of 71% while the average ratio of the longer weekly values increases to 81%. The differences are likely due to a bias towards large interception percentages for individual rainfall events that are relatively small in total depth (e.g. < 3 mm) and also make up a rather large percentage of one third of all rain producing events. Removing events less than 3 mm in total size yields an average throughfall ratio of 79% for the larger events while an average of only 56% of the total rainfall reaches the ground during these smaller events. Summing the total volumes for all events yields a ratio of 83%.

Statistics for each individual storm are given in Table 2 and reported graphically by Fig 2. Longer term volumetric comparisons made on a weekly basis are alternatively shown in Fig 3. Both plots of precipitation suggest a constant throughfall fraction irrespective of storm size, particularly at lower rainfall amounts. At the longer weekly time step this observation appears to be even more appropriate. In practice the actual throughfall percentage at the event level is extremely complicated and dependent upon a number of factors such as rainfall duration, intensity, and atmospheric conditions to name a few. The literature is abound with different modeling techniques to estimate throughfall. However there is significant variance between methods that justifies new observations.

	Mean	Median	Std Deviation	Minimum	Maximum
Throughfall [mm]	7.4	3.6	10.0	0.5	43.7
Gross Rain [mm]	8.9	4.8	10.8	0.6	49.0

Table 2 Statistics for 73 individual rainfall events used to compute throughfall percentages.

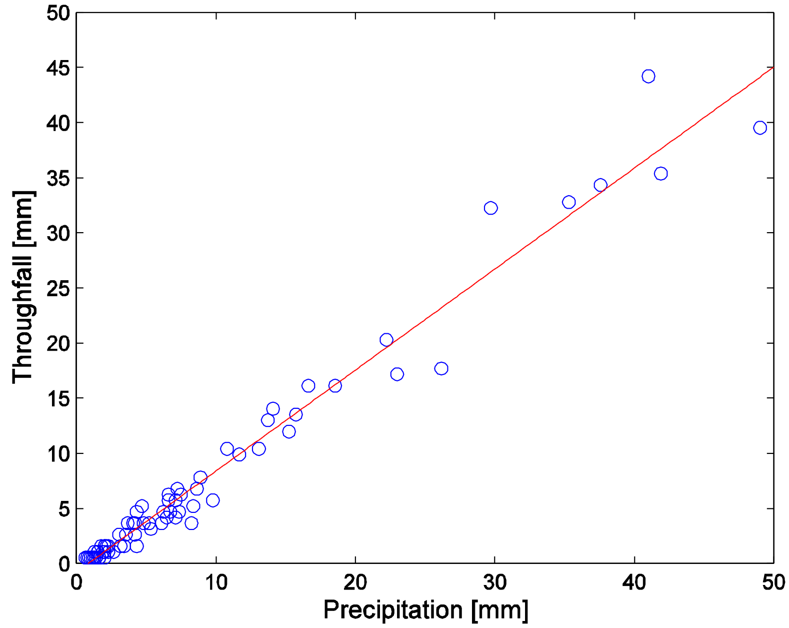

Fig 2 Total precipitation volumes plotted against throughfall for a total of 73 individual rainfall events.

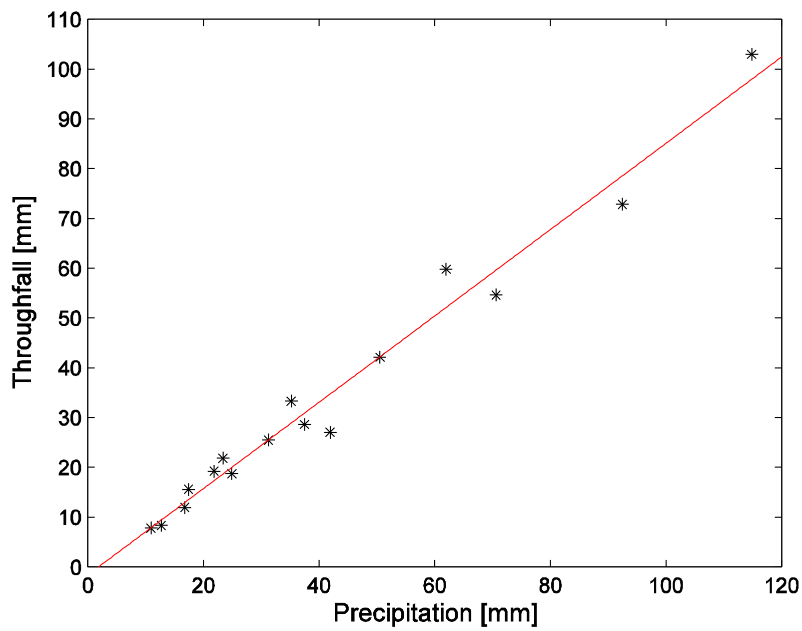

Fig 3 Weekly accumulations of rainfall and throughfall for a total of 16 weeks.

Soil Properties

Unsaturated hydraulic conductivity was undertaken at three positions on the Cerro Pelado hillslope: ridge top (just upslope of soil pit 1), mid-slope (adjacent to soil pit 4), and valley bottom (vicinity of groundwater well 4). Based on the amount of time involved in the infiltration of large

negative tensions we subjectively decided to focus on tensions of: -0.5, -1.0, and -2.0 cm for all measurements. For all three sites multiple measurements with these tensions were taken at the ground surface. Dependent upon the particular location additional measurements were taken at varying depths to gain further understanding on the potential controls of infiltrating water. Of course we should proceed cautiously when discussing a specific value to be representative of hydraulic conductivity because soils are highly heterogeneous in manner.

Correctly siting the infiltrometer below 30 cm on the ridge top was not permissible due to increased presence of large rocks. Therefore, measurements at this location were taken at the soil surface, 13 cm, and 30 cm depths. While we do not have measurements of hydraulic conductivity at further depths we can glean from Fig 4 and Table 3 that the infiltration rate has probably decreased one order of magnitude in the top 30 cm. It is interesting to note that the conductivity appears to be lowest at a depth of 13 cm with the average of 11 cm/h compared to the surface value of 50 cm/h. Comparing the maximum values at each of these depths we see an order of magnitude drop from 130 to 22 cm/h. At 30 cm depth K_{sat} has increased slightly, but we can not definitely say that it is a significant change.

	Mean	Median	Std Dev	Minimum	Maximum	N Samples
0 cm	49.7	40.8	44.1	9.7	130.0	6
13 cm	11.2	12.6	7.6	1.4	21.5	5
30 cm	17.8	16.3	9.7	8.7	30.1	4

Table 3 Summary of statistics for infiltration tests performed at the ridge top location; cm/h.

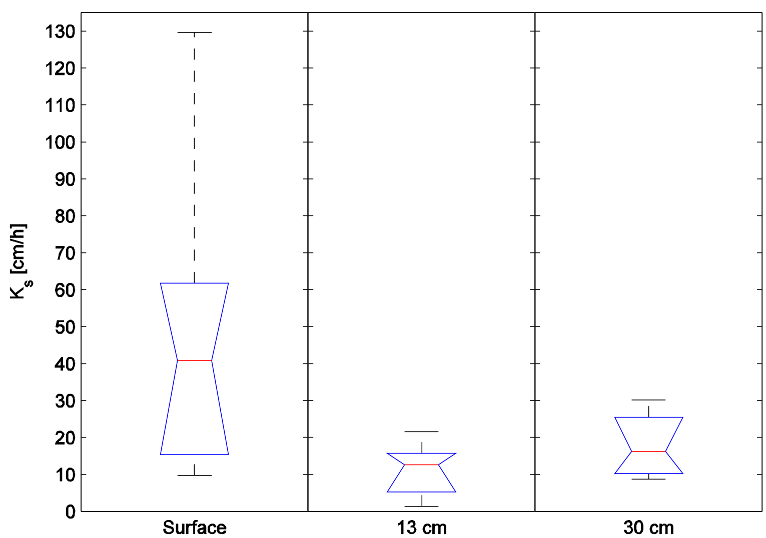

Fig 4 Saturated hydraulic conductivity as a function of depth at the ridge top.

At the midslope location it was possible to take three readings at depths of 0 cm, 30 cm, and 90 cm as shown in Fig 5 and Table 4. Compared to the most upslope position the surface infiltration is somewhat lower. There is significant variation in soil hydraulic properties along the hillslope, as seen by comparing Figures 4 through 6.

	Mean	Median	Std Dev	Minimum	Maximum	N Samples
0 cm	22.5	22.8	3.7	18.6	26.0	3
30 cm	8.0	5.8	5.2	4.8	15.7	4
90 cm	5.8	7.2	3.4	0.9	9.1	5

Table 4 Infiltration summary statistics for the midslope location; all reported values are given as cm/h.

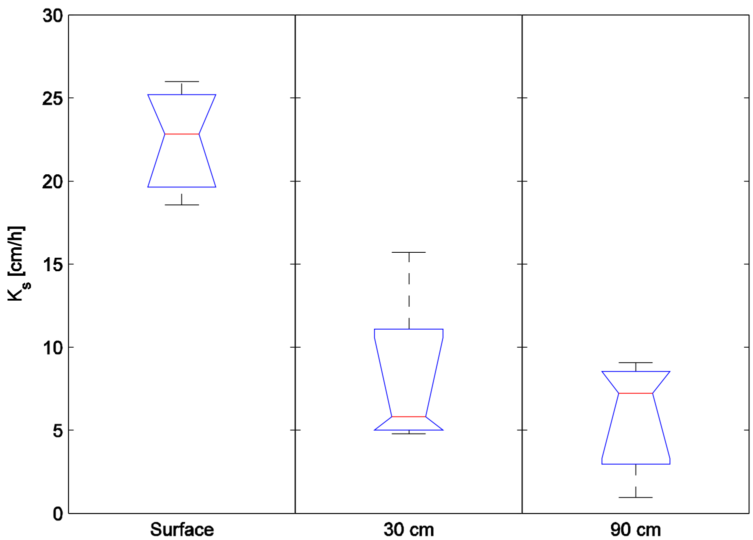

Fig 5 Saturated hydraulic conductivity as a function of depth at the midslope location.

Lastly, we decided to only investigate the soil surface at the valley bottom location since the impeding layer appears to be located at the surface. During installation of groundwater wells in this area it became apparent that the soil was uniform with depth. This area shows evidence of frequent overland flow and it was expected that a much lower mean hydraulic conductivity would be found. Results from this location are tabulated in Table 5 and shown graphically in Fig 6.

	Mean	Median	Std Dev	Minimum	Maximum	N Samples
0 cm	2.1	2.0	1.6	0.6	3.8	3

Table 5 Infiltration summary statistics for the valley bottom location; all reported values are given as cm/h.

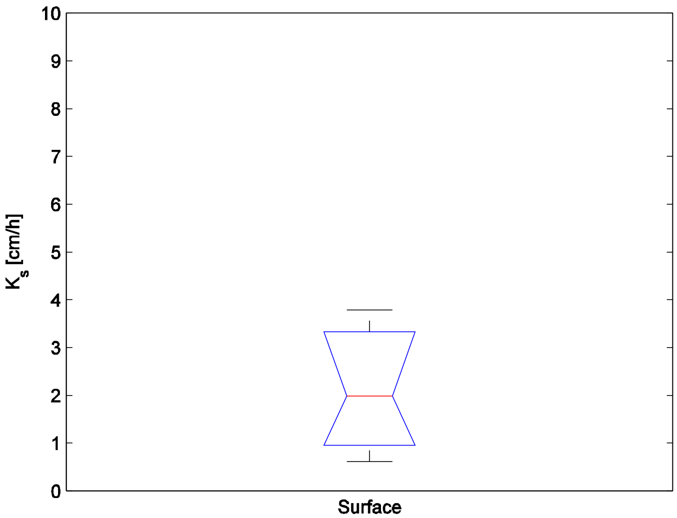

Fig 6 Saturated hydraulic conductivity at the soil surface in the valley bottom; at this location the confining layer appears to be at the ground surface and is uniformly distributed with depth.

Evapotranspiration

Thirty minute values of latent heat fluxes were rigorously screened for anomalous data flags to ensure the best possible daily estimates of evapotranspiration. In such a manner unusual data was filled with a half hour estimate from the Priestly-Taylor method previously described. To help evaluate the overall utility of the Priestly-Taylor method daily ET estimates from both methods were compared during dry periods where there were no gaps in the data. A linear fit to the data in Fig 7 indicate that the Priestly-Taylor method is slightly biased toward an under prediction of ET. The Priestly-Taylor methods shows a nearly uniform spread in either direction about the trend line.

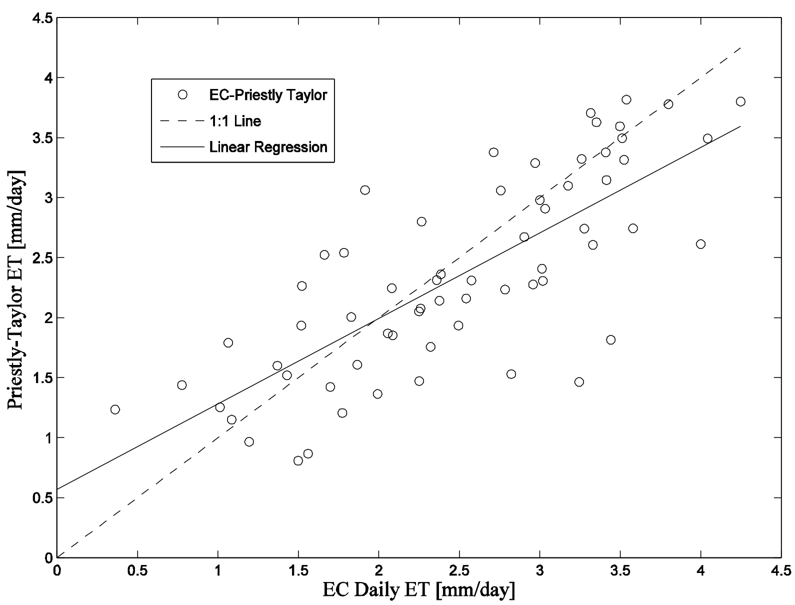

Fig 7 Comparison of daily values of ET from the eddy covariance and Priestly-Taylor methods, a linear fit to the data suggest the Priestly-Taylor method shows a slight bias.

Half-hourly measurements of ET [mm] after being gap filled were then summed over the entire day to provide daily values.

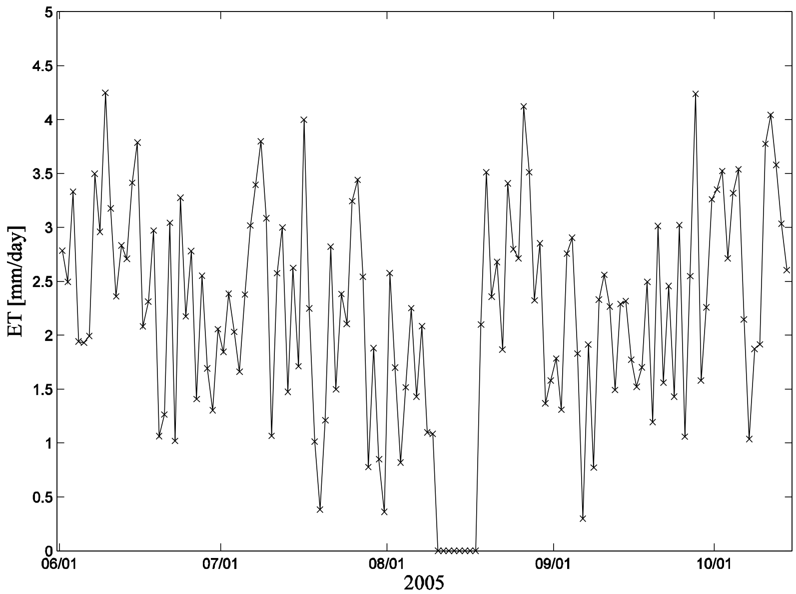

Fig 8 Daily estimates of ET after adjustment for anomalous data, a gap of eight days due to power loss is shown in mid-August as the values equal to zero.

Conclusions

During this study, an extensive data collection network was installed in very rugged tropical terrain. Approximately six person-months were spent by the P.I. and graduate students in Panama during 2005 installing instrumentation, collecting field observations, and testing hypotheses. The data collected to date provide an indication of the relative importance of different processes, and improves our process-level understanding. Analysis of the data is ongoing at the time of the writing of this report. Several peer-review publications are in preparation.

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Appendixes